Research Laboratory
of the
Portland Cement Association

BULLETIN 5

A Working Hypothesis for Further Studies of Frost Resistance of Concrete

BY
T. C. POWERS

FEBRUARY, 1945
CHICAGO

Authorized Reprint from Copyrighted
JOURNAL OF THE AMERICAN CONCRETE INSTITUTE
New Center Building, 7400 Second Boulevard
Detroit 2, Michigan
February 1945, PROCEEDINGS *V. 41, p. 245*

A part of PROCEEDINGS OF THE AMERICAN CONCRETE INSTITUTE Vol. 41

JOURNAL
of the
AMERICAN CONCRETE INSTITUTE

Vol. 16 No. 4 7400 SECOND BOULEVARD, DETROIT 2, MICHIGAN February 1945

A Working Hypothesis for Further Studies of Frost Resistance of Concrete*

By T. C. POWERS†
Member American Concrete Institute

SYNOPSIS

Basic information is given on the freezing of water in concrete. From this information and other published material an explanation of the mechanism of the action of frost on concrete is developed. The explanation takes into account such factors as the degree of saturation of the concrete, the permeability and strength of the concrete, hydraulic pressures generated during freezing, and air-filled cavities. It is suggested that the hypothesis be made the basis of further laboratory studies of the action of frost in concrete.

INTRODUCTION

Laboratory testing of concrete to predict its ability to resist frost action has been carried on for many years. Nevertheless, no generally satisfactory testing technique has been developed; different laboratories testing the same kind of concrete often obtain different results and even in a given laboratory seemingly contradictory results are not uncommon. Thus, we still have a problem of developing a suitable testing technique and basis for interpretation of the results.

The writer has no ready-made solution of this problem to offer, but from the writings and experiments of others and from fundamental studies carried on in this laboratory it is possible to set up a working hypothesis which, together with other hypotheses, may eventually lead to the desired solution.‡ To the writer a working hypothesis such as this is not something to be accepted because it appears reasonable or rejected because it conflicts with previously acquired concepts and therefore appears unreasonable. Rather, it should be a logical development of certain major premises. The development should be such as to point out various implications of the premises and thereby to suggest experi-

*Received by the Institute Dec. 30, 1944.
†Manager of Basic Research, Portland Cement Assn., Chicago
‡Many of the ideas presented here are elaborations of those given by W. C. Hansen (Office memorandum, P. C. A. Research Laboratory).

mental procedures for testing the premises. The hypothesis presented in this paper rests mainly on the premise that the destruction of concrete by freezing is caused by hydraulic pressure generated by the expansion accompanying freezing of water rather than by direct crystal pressure developed through growth of bodies of ice crystals. If this premise is a fact, then various other things brought out in the discussion should be true. But, obviously, if the premise is false, the deductions are likewise false. It is hoped that attempts will be made to test the premises experimentally. Such attempts should lead to new approaches in the study of durability; if they do, the purpose of this paper will have been accomplished.

The hypothesis rests partly on certain as yet unpublished data on the structure of hardened portland cement paste and on the properties and behavior of the evaporable water that the paste may contain. It is necessary, therefore, to set down this information in order that the hypothesis may be correctly understood. No attempt will be made here to justify or qualify the various statements made about the structure of the paste; that must be done in other papers. Consequently, the discussion will unavoidably appear to be somewhat dogmatic.

Structure of cement paste

The hydration products are visualized as a porous gel enveloping unhydrated clinker and some non-colloidal hydration products, principally calcium hydroxide.* The porosity of the paste presents two aspects: First, there is the porosity of the gel-substance itself; second, there is the residual space unfilled by gel. The average size of the pores in the gel-substance is indicated as being about 8 times the diameter of a water molecule. When this porous gel-substance, together with the other solids, completely fills the available space, the only pores remaining in the paste (except entrained bubbles) are the extremely minute pores of the gel itself. When, however, the gel does not fill the original space completely, as is always the case in practical concrete, the paste is permeated by a system of submicroscopic, interconnected capillary spaces that are thought of as residues of the originally water-filled space. The exact manner in which the gel is laid down is not yet clear, but at present it seems most probable that the gel deposits mainly in the regions nearest the original cement particles and that therefore any residual space will be in regions that were at greatest distances from the original cement grains. The pattern of the capillary system is therefore determined by the original paste structure.

In the course of hydration the capillaries, at first full of water, become partially emptied as a result of contractions in volume that accompany

*L. T. Brownmiller, "The Microscopic Structure of Hydrated Portland Cement," ACI JOURNAL, Jan. 1943; *Proceedings* V. 39, p. 193.

hydration, studies of which have been reported from this laboratory and others.* They do not readily refill by absorption of water from the outside even though the specimen may be stored under water.

When small particles of cement paste are dried, the particles undergo a permanent, irreversible shrinkage. The shrinkage is such that in a paste having a water-cement ratio of about 0.5 by weight the hardened paste can reabsorb only 95 percent of the volume of water it was originally capable of holding. On the other hand, when a specimen of *concrete* containing a similar paste is dried, it is capable of reabsorbing more water than it lost initially. (This is probably due to the restraints against shrinkage offered by the aggregate particles.) Nevertheless, a specimen does not become fully saturated by absorption alone, probably because the extremely dense material desiccated during hydration is difficult to penetrate, and because of entrapped air.

The partial emptying of the capillaries during hydration is believed to be an important factor contributing to whatever degree of resistance to frost a concrete may show. This conclusion is based on the results of experiments which showed that when the air is removed from a dried specimen before introducing water, thus permitting the water to saturate the paste, a specimen normally able to withstand 100 or more cycles of freezing and thawing will disintegrate completely in less than 5 cycles. *Therefore, it may be concluded that when a specimen known to contain freezable water is able to withstand many cycles of freezing and thawing, its water content was initially below some critical value, that may be called the critical degree of saturation.* This, of course, is the same idea that has been set forth by Kreüger† and others.

As has been found for other porous building materials, a specimen of concrete will fail completely on freezing when its degree of saturation exceeds some critical value that is probably somewhere near 90 percent of saturation; but, as will be shown presently, concrete is of such nature that it can be damaged by repeated freezings before it reaches the critical degree of saturation.

Freezing temperatures

The highest temperature at which ice can exist in concrete depends on the degree of saturation of the concrete, or more fundamentally, on the forces acting on the freezable water. The magnitude of the forces is indicated by the relative vapor pressure of the evaporable water in the concrete. When concrete is saturated, or virtually so, the melting point is only slightly below 32 F, the amount of depression depending

*F. M. Lea and C. H. Desch, *The Chemistry of Cement and Concrete* (New York: Longmans, Green & Co., 1935), p. 175; W. C. L. Hemeon, "Setting of Portland Cement," *Ind. Eng. Chem.* 27, 694 (1935); T. C. Powers, "Absorption of Water by Portland Cement Paste during the Hardening Process," *Ind. Eng. Chem.* 27, 790 (1935).

†H. Kreüger, Transactions of the Royal Swedish Institute for Scientific-Industrial Research, No. 24, 1923, Stockholm.

on the concentration of soluble salts in the freezable water. When a saturated, hardened paste is cooled sufficiently, water held in the hardened paste will freeze, but unlike pure water in bulk, not all of it will freeze at the same temperature. This, of course, would be the effect expected of dissolved salts, but the effect is very much greater than can be accounted for by dissolved salts and is in fact a direct effect of the colloidal nature of the hydration products. This effect is such that the amount of ice formed in a given saturated specimen is an inverse function of the temperature, the lower the temperature the greater the amount of ice formed.

On raising the temperature, the ice disappears progressively and, in a saturated specimen, will be completely melted at a temperature slightly below 32 F.

Amount of freezable water

By a dilatometer method to be described in another paper the amounts of freezable water in various saturated pastes have been measured in this laboratory. The results can be expressed in the following general form:

$$w_f = w_t - kw_n \qquad (1)$$

where w_f = weight of freezable water at a given temperature

w_t = weight of total water in sample, including non-evaporable water

w_n = non-evaporable water

k = a constant which varies slightly with the type of cement and with the freezing temperature.

The non-evaporable water, w_n, is defined as that which exhibits vapor pressure less than about 4×10^{-4} mm of mercury at 23 C. This is the vapor pressure of the system $Mg(ClO_4)_2.2H_2O + Mg(ClO_4)_2.3H_2O$ at 23 C. w_n is about 10 percent more than the amount of "fixed water" held by a sample oven-dried at 105 C under average atmospheric conditions.

From Equation 1 it follows that when $w_f = 0$, $w_t = kw_n$. We may designate this particular value of w_t as w_t'. For a given cement and freezing temperature w_t' is thus seen to be proportional to the extent of hydration of the cement.

The proportionality factor k was evaluated from tests made on five different cements. The data were obtained from samples taken from a group of specimens comprising three different mixes (w/c = 0.3 to 0.6) and two curing periods (28 and 90 days) for each cement. The average value of k was obtained by a short extrapolation of a straight-line plot and was found to be 1.75. This value shows that for a saturated paste to be free from water freezable at − 15 C, which is virtually all the freezable water, the total water content must not be more than about 1.75 times

the non-evaporable water content. This means also that the *un*freezable part of the evaporable water is a quantity equal to about ¾ of the non-evaporable water content.

Since the total water content of a saturated paste is limited by the original water-cement ratio, the above figures indicate that if the original water-cement ratio is properly limited the paste will be free from freezable water after hydration. The limit will be higher the greater the extent of hydration. The original water ratio is not indicated directly by these figures, however, since the total water content includes the gain that occurs during the curing period and is therefore larger than the original water content. For estimating the amount of freezable water in terms of the original water content, w_o, the following empirical relationship was found to hold:

$$w_f = m(w_o - K\,w_n) \quad \ldots\ldots (2)$$

where m is an empirical constant. Its average value was found to be 1.16. K has the same significance as k in Equation 1 but is numerically smaller. When $w_f = 0$

$$w_o' = K\,w_n$$

where w_o' is the original water content of a paste having no freezable water after hydration. The average value of K was found to be 1.3.

The values of w_o' can be determined from the extent of hydration as measured by the non-evaporable water content. The value so determined for cements of average composition was found to be about 0.30 g per g of cement for specimens cured 28 days, and about 0.32 g per g of cement for those cured 90 days, the average non-evaporable water contents being 0.230 and 0.246 g per g of cement, respectively.

These values indicate the maximum original water-cement ratios for pastes having no freezable water after hydration. Since all practical concrete is made with higher water-cement ratios than these, it contains, or is capable of containing, freezable water. The quantity of freezable water can be estimated from Equation 2. For purposes of estimation, this may be written

$$w_f = 1.16\,(w_o - 1.3\,w_n) \quad \ldots\ldots (3)$$

For example, if $w_o/c = 0.5$,

then $\quad w_f/c = 1.16\,(0.5 - 1.3\,w_n/c)$.

When $w_n/c = 0.2$, $w_f/c = 0.28$ g per g of cement.

The data given above all pertain to samples cured at normal temperatures. If a high curing temperature is used, the relationships are much different from those just described.

Situation of ice in concrete

The spaces in undamaged concrete that may absorb and hold water are believed to be as follows:

(1) Spaces within the gel substance itself;
(2) The capillary system within the mass of gel substance;
(3) The capillary system in absorbent aggregate particles.

Analysis of adsorption isotherms and studies of the density of the evaporable water (to be reported in other papers) both indicate that in a saturated paste, a quantity of evaporable water 0.75 to 1.0 times the quantity of non-evaporable water is "gel water" as distinct from "capillary water."* As shown above, independent measurements of freezable water showed that the *un*freezable water is an amount equal to about 0.75 times the amount of non-evaporable water. This may be considered as experimental evidence that the ice formed in the paste occurs only in the capillary system within the gel substance. The capillaries are thought of as residues of the original water-filled space not filled by gel and hence are probably pocket-like but apparently interconnected.

Besides this experimental evidence there are some indirect indications that ice is not likely to form within the gel substance. The average specific volume of the water in the gel is about 0.85. This indicates that all or most of it is within the range of the surface forces of the solid phase and that therefore the spaces in which the water is held are exceedingly small. In fact, there is reason to believe that the relationship between the gel water and the gel substance is not much different from solid solution. The probability of nuclei formation in water held in such a state is much lower than it is in the larger capillary spaces where, when the paste is saturated, the water is under no stress.

Ice probably does not form in the macro- or even microscopic cavities of an undamaged specimen. Such cavities, surrounded by absorbent paste, can contain no water until some force such as that arising from expansion on freezing displaces water from the surrounding paste into the cavity.

Besides forming in capillaries within the paste ice may form also in the capillary system of absorbent aggregate particles.

MECHANISM OF DISINTEGRATION

When concrete specimens are frozen and thawed in water, two distinct types of disintegration have been observed: (1) The specimens may show little change in weight and appearance but large losses in strength and resilience; or (2) they may show progressive loss by crumbling and spalling but relatively little loss in strength and resilience of the remaining material. These are extremes. Specimens falling in neither category will show both crumbling and loss of strength and resilience of

*Evaporable water is defined as that having a vapor pressure at 23 C. greater than about 4 x 10^{-4} mm of mercury.

the remaining material. These are results that an acceptable hypothesis must explain satisfactorily.

Generation of hydraulic pressure

Ordinary ice can exist under pressures up to about 29,000 psi., but of course not at 32 F. At 32 F the pressure cannot exceed 1 atmosphere, but for each Fahrenheit degree drop in temperature below the normal melting point the pressure may be increased about 736 psi., up to the maximum mentioned, which is reached at about −4 F.* For example, at 13.5 F ice can exist under a pressure of about 10,000 psi.; or, to put it another way, a pressure of about 10,000 psi. would be required to prevent the formation of ice at 13.5 F if conditions are otherwise such that the ice could exist at 32 F under a pressure of 1 atmosphere.

The above remarks give the magnitude of pressures that would be exerted on a piston closing a water-filled cylinder if the piston were held so as to prevent the expansion that accompanies freezing. It is thus indicative of the magnitude of the pressure that might develop in a completely saturated, sealed specimen of concrete.

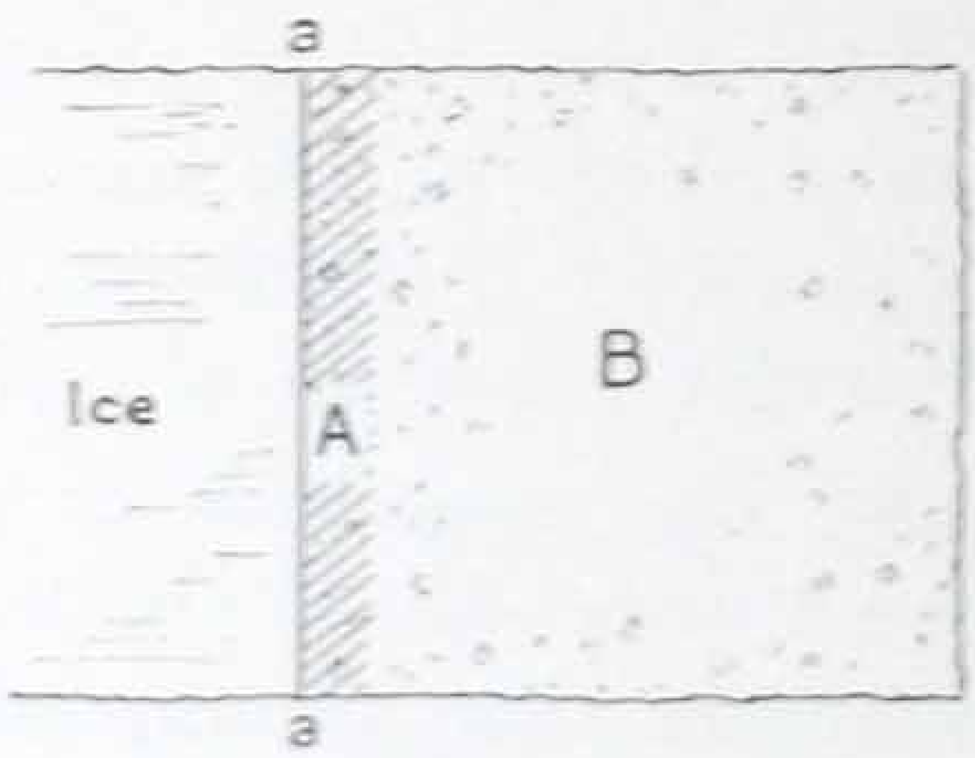
Experiments show that fully saturated concrete (saturated with the aid of a vacuum pump) is not able to withstand the pressures that are developed at the low temperatures used in freezing and thawing tests. This shows that concrete is not sufficiently extensible to undergo the strains that would be necessary to relieve the pressure. Hence, we may conclude that since *apparently saturated* concrete does not ordinarily fail completely on first freezing it is not fully saturated, even after prolonged soaking. That is, ordinarily there is enough residual space in the concrete to accommodate the expansion that accompanies freezing. Nevertheless, under certain conditions some specimens show loss of resilience and abnormal expansion on repeated freezing and thawing even though they are not fully saturated; that is, they are damaged by freezing even when the degree of saturation of the specimen as a whole is below the critical value that would cause bursting and complete disintegration. For a working hypothesis to be satisfactory it must account for this fact. The following discussion is an attempt to meet this requirement.

Consider a surface of a specimen that has been in contact with water for some time prior to the beginning of the freezing cycle. The water content of the concrete near the surface is probably at or near total saturation, and is higher, though perhaps only slightly, than the average water content of the specimen. If this surface is so situated that heat from the concrete flows through it to the surrounding water, the sequence of events should be as follows: First, the water against the surface will

*N. E. Dorsey, *Properties of Ordinary Water Substances* (Reinhold Publishing Corp., 1940), p. 467.

freeze, thus sealing the surface of the concrete; second, the water in the capillary spaces of the concrete nearest the surface will freeze and as the change of state takes place the still unfrozen water in the saturated region will be displaced towards the less saturated interior. This may be visualized with the help of Fig. 1. The drawing represents a cross-section of a part of the specimen, the surface in question being normal to the plane of the page at aa. A is the saturated region near the surface; B is the region of lower water content.

Fig. 1



Ice will form on the outside of the surface before any will form in the specimen because of the depression of the freezing point mentioned above and perhaps because of the tendency for the water in the concrete to supercool. Freezing will occur in A before it does in B, because of the direction of the temperature gradient, and because A is at a higher water content than B and hence because the water in A can freeze at a higher temperature than the water in B.

When ice begins to form in region A, the unfrozen water will be displaced toward the less saturated region B. If the water were free to move without resistance, no hydraulic pressure whatever would develop. However, since the water is required to move through a fine-textured, porous substance, the force causing the movement will give rise to a corresponding frictional (viscous) resistance and gradients of hydraulic pressure will be present during the movement of the water according to the laws of hydraulic flow.

If this reaction against the force displacing the water inward is sufficiently high, then it can be regarded as being capable of damaging the specimen. The possible magnitude of the hydraulic pressure can be estimated on the basis of published data on the permeability of concrete. For concrete having a water-cement ratio of 0.6 by weight, cured 28 days, the coefficient of permeability is about 40×10^{-12}.* Hence, by Darcy's law,

$$Q = 40 \times 10^{-12} \times \frac{H}{L}$$

*A. Ruettgers, E. N. Vidal and S. P. Wing, ACI JOURNAL, Mar.-Apr., 1935; *Proceedings* V. 31, p. 382.
NOTE: The unit of permeability used here is cu. ft. of water per sq. ft. of concrete per second per foot of head per foot of thickness.

where Q = rate of flow through the concrete, ft. per second
H = pressure-drop through the layer, ft. of water
L = thickness of layer, ft.

If we assume a given rate of water movement (corresponding to a given rate of freezing), then we can compute the required difference in pressure over a given thickness of the region through which the water is being forced. However, for the present purpose it is advantageous to estimate the rate of movement required to develop a reacting pressure sufficient to damage a specimen of concrete. If we assume that the concrete has a tensile strength of 500 psi. and that the mobile water contacts 10 percent of the cross-section, then it would follow that a hydraulic pressure of 5000 psi. would be required to produce an average stress equal to the strength of the concrete. However, the specimen would probably be damaged at a lower hydraulic pressure since stresses adjacent to the source of pressure would be well above the average. It seems safe to assume that a pressure of 2500 psi. would be destructive. (Such a pressure could be developed at any temperature below about 28.5 F.)

With this assumption regarding the magnitude of a damaging pressure we can compute the velocity with which the water must be forced through a given thickness to give rise to reacting hydraulic pressure of destructive magnitude. If the layer through which the water moves is 0.001 ft. (0.012 in.), then to develop a reacting pressure of 2500 psi. (5800 ft.-head), the rate of flow would be

$$Q = \frac{40 \times 10^{-12} \times 5800}{10^{-3}}$$

$$= 232 \text{ millionths of a ft. per sec.}$$

$$= 10 \text{ inches per hour.}$$

A rate of flow of 10 inches per hour would correspond to a rate of ice formation of about 100 inches per hour. Such a high rate of freezing is improbable, even under laboratory conditions; hence, if damage results from freezing through the resistance to movement of water, the thickness of the layer through which the water is forced to move must be considerably in excess of that assumed in the above computation, 0.012 inches. Since the velocity necessary to develop a given reacting pressure is inversely proportional to the thickness of the region through which the water is being forced, the required rate for different thicknesses can be readily seen from the above computation. For example, if the thickness is 10 times that assumed, 0.12 instead of 0.012, the rate of flow would be 1 inch per hour and the rate of freezing about 10 inches per hour; or if the thickness were 0.24 inches, the rate of water movement would be ½ inch per hour and the rate of freezing, 5 inches per hour, and so on.

Depths of saturation in excess of ¼ inch and rates of freezing of the order last mentioned are well within the range to be expected in many laboratory freezing tests. Hence, to consider the reacting hydraulic pressure accompanying water movement as a possible source of disruptive pressure is in line with experimental data on the tensile strength and degree of permeability of concrete. It indicates a possible mechanism whereby a specimen of concrete can be damaged by freezing even though it may not be saturated to the critical degree.

In connection with the frost heaving of soils, Stephen Taber* has described another mechanism of pressure development in porous bodies that are not fully saturated. In soils that are not too highly impermeable or that are not carrying too great a superimposed load or that are not cooled too rapidly, pressure is developed by the formation of segregated bodies of ice crystals which grow in a direction parallel to the heat flow by receiving water from the unfrozen interior. This theory will be discussed more fully in a later section of this paper. At this point it will suffice to say that the writer believes that the same reasoning and experiments which demonstrated the soundness of Taber's theory with respect to the behavior of certain soils leads to the conclusion that the same phenomenon is not likely to occur in concrete, at least under the conditions of laboratory freezing and thawing tests. Consequently, the hypothesis here developed is based on the assumption that hydraulic pressure is the primary disruptive force. In Taber's language, the assumption is that concrete behaves as a closed system whereas some soils behave as open systems; and the thought is here added that in a porous body which acts as a closed system disruptive back-pressure may be developed by motion of the water even when there is enough room within the body to accommodate the total expansion. However, the phenomenon described by Taber is probably not entirely absent, as will be brought out later.

Crumbling and spalling

On repeated freezing and thawing in water, region A should increase in thickness according to the amount of water absorbed by the specimen. As the thickness of region A increases, the resistance to displacement of water out of that region toward the region of lower water content will increase, and when the saturated region becomes sufficiently thick the hydraulic pressure will become greater than the strength of the material and cause disintegration or spalling of some part of region A. The thickness of region A at the time when disintegration in region A begins is as *the critical depth of saturation* mentioned before.

The concept of critical depth of saturation as given above is a somewhat oversimplified picture, for in reality the saturated region is not

J. Geol. 37, 428 (1929); *38*, 289 (1930); *Public Roads 11*, 113 (1930).

sharply separated from the other; instead, the two regions are joined by a transition zone where there is a continuous moisture gradient. Moreover, the saturated region is seldom if ever completely saturated; even after prolonged soaking it contains spaces into which water can be forced by high pressure. However, the simplified version will serve the purpose of this discussion.

One of the implications of this concept is that if a specimen were uniform in structure (homogeneous, in a restricted sense) and not wholly saturated at the start, no crumbling or spalling would result from freezing until a certain amount of water had been absorbed, such as to saturate the surface region to the critical depth.

The critical depth of saturation should be different for different grades of concrete because the magnitude of the hydraulic pressure and the average stress produced will depend on the following factors:

(1) The hydraulic pressure will depend on:
   - (a) The permeability of the material through which water must flow to escape from the saturated region.
   - (b) The rate of freezing.
   - (c) The amount of water in region A in excess of the critical degree of saturation.

(2) At a given hydraulic pressure the average stress in the concrete will depend on the proportion of solids in a unit cross-section.

The degree of permeability (item (1a) above) should have a marked effect on the intensity of hydraulic pressure generated in the saturated region during freezing. The following illustration will show how this comes about:

The amount of freezable water in saturated paste can be estimated from the empirical relationship given before:

$$w_f/c = 1.16\ (w_o/c - 1.3\ w_n/c)$$

For an average cement cured 28 days, w_n may be assumed to be 0.22. Hence,

$$w_f/c = 1.16\ (w_o/c - 0.29)$$

With the aid of this relationship the following table was prepared:

Properties of the Concrete (Estimated or Assumed)	Rich Mix	Lean Mix
Cement content, lb. per cu. yd.	610	390
w/c by weight	0.45	0.70
Freezable water content at saturation:		
lb. per cu. yd.	115	186
cu. ft. per cu. yd.	1.85	2.98
cu. ft. per cu. ft.	0.068	0.110
Coefficient of permeability*	2×10^{-12}	150×10^{-12}
Tensile strength, psi	600	300

*Ruettgers, Vidal, and Wing; *ibid.*

If water is forced through a thickness of 0.001 ft. at the rate of 1 inch per hour (= 23.2×10^{-6} ft. per sec.), the respective pressures developed as computed from Darcy's law are:

Rich concrete	5020 psi
Lean concrete	67 psi

These figures are, of course, significant only on a relative basis, since the rate and thickness are arbitrarily chosen figures. However, since the rate of freezing is probably not appreciably influenced by the quality of the concrete, and since a given distance of flow could be found in either quality, the pressures indicated should be in substantially correct ratio.

To illustrate how the permeability and strength determine the critical depth of saturation, the following computation is given, based on an assumed rate of water-movement of 0.1 in. per hour.

The average stress in each concrete will be

(unit-hydraulic-pressure) $\times$ (fractional area contacted by the mobile water)

or $502 \times 0.068 = 34.0$ psi for the rich concrete

and $6.7 \times 0.110 = 0.7$ psi for the lean concrete,

this computation being based on a depth of saturation of 0.001 ft. Since, at a given rate, pressure is inversely proportional to depth of saturation, the depth of saturation at which the average stress equals the tensile strength is

$(600 \div 34.0) \times 0.001 = 0.0176$ ft. $= 0.21$ in.

for the rich concrete, and

$(300 \div 0.7) \times 0.001 = 0.43$ ft. $= 5.2$ in.

for the lean concrete.

It must be emphasized that the absolute values given may be far from the actual facts; they serve only to illustrate the principle on which the hypothesis is based. For example, if the actual rate of movement is 1/10 that assumed, the thickness required for a given average stress is 10 times the value given. It must be borne in mind also that the computations rest on the assumption that the region where ice is forming is fully saturated. This condition is probably never fulfilled; hence, the computations represent a limiting case.

These figures might seem to indicate that a rich concrete should show more crumbling or spalling than a lean one, since in this case the critical depth of saturation of the rich mix is only one-twenty-fifth that of the lean; it looks as if the rich mix might show surface disintegration earlier than the lean one. However, to reach such a conclusion would be to ignore common experience and to overlook the great difference between the rates of absorption of such concretes; the lean concrete absorbs water much more rapidly. Moreover, rich concretes do not become fully saturated, even on prolonged soaking, unless capillary action is augmented by the forces produced on freezing. Note also that even if it took similar lengths of time for the two grades of concrete to become saturated

to their respective critical depths, the loss per cycle per unit area from the leaner concrete would be much greater than that from the richer.

It is important to note in this connection that under natural conditions of exposure, concrete is usually subjected to alternate wetting and drying as well as freezing and thawing. If the periods of drying are long relative to the period of wetting, dense, impermeable concrete manages to remain at a low percentage of saturation as compared with that of low-grade concrete which absorbs water quickly. Moreover, impermeability is usually the result of using a high cement content and hence such concrete reaches a higher degree of desiccation through the contractions that accompany hydration.* These advantages, particularly the advantage of a low rate of absorption, are not always brought out in laboratory tests where small specimens are used.

Item (1c) above concerning the degree of saturation requires special comment. Theoretically, if the water content of region A is about 90 percent of saturation or less, then all the expansion can be accommodated without any of the water escaping from A. If the water content exceeds 90 percent of saturation, then the excess must escape or region A will disintegrate; the greater the excess the greater the amount of water that must escape in a given length of time; hence, the greater the hydraulic pressure developed.

If in a given specimen the critical depth of saturation happens to be equal to or greater than half the thickness of the specimen, then disintegration should not begin until the entire specimen reaches the critical state of saturation. Such a specimen should show little or no disintegration during the cycles required to bring it to the critical state, but when that state is reached the specimen should disintegrate almost completely in a few final cycles. This apparently accounts for the observed behavior, mentioned earlier, of those specimens that show little change in weight or appearance, but, in a final few cycles, rapidly lose all strength and resilience. Such specimens are the relatively coarse-textured ones of high permeability.

Damage without disintegration

The critical depth of saturation discussed above pertains to the depth to which the surface region must be saturated before surface disintegration takes place. Extension of the same principles cited before leads to the conclusion that concrete may also be damaged even in regions where expansion on freezing could be accommodated by available space within the region.

---

*For a discussion of the importance of this phenomenon see M. A. Swayze, "Early Concrete Volume Changes and Their Control," ACI Journal, Apr. 1942; *Proceedings* V. 38, p. 425.

The disruption of porous, water-laden aggregate particles is sometimes responsible for this; water in a particle is trapped by ice or by relatively impermeable paste surrounding the particle, and the hydraulic pressure generated by freezing disrupts the particles and expands the specimen. However, a similar result in the absence of such aggregate particles is conceivable. Even if the paste is not saturated to the extent where pressure causes disruption, the pressure may still be high enough to cause some dilation. Such an effect in a low-w/c concrete might develop at a lower degree of saturation than in a high-w/c concrete. This is suggested by the figures given above on relative intensities of hydraulic pressure as controlled by permeability. In the example given, it can be seen that a condition that would develop negligible pressure in a lean mix might develop pressures high enough to cause dilation of a richer mix.

Some experimental evidence supporting this is given in Fig. 2. This represents 3x3x15-in. concrete prisms (0-¾ in. aggregate) that had been cured in the moist room 7 days, stored in air at 50 percent relative humidity for 6 weeks, and then soaked in water 4 days just before the beginning of the freezing and thawing test. Note that the richest specimens showed relatively little loss in weight but relatively high expansion and drop in Young's modulus. For example, after 100 freezings and thawings, the concrete prisms containing 4 sacks of cement per cubic yard showed 0.1 percent increase in length and those containing 7 sacks showed 0.3 percent increase. The apparent decreases in Young's modulus were 28 and 65 percent, respectively. However, the surface disintegrations compare quite differently; the weight loss of the leaner concrete was about 8 percent and that of the richer, 2 percent. The relative weight losses

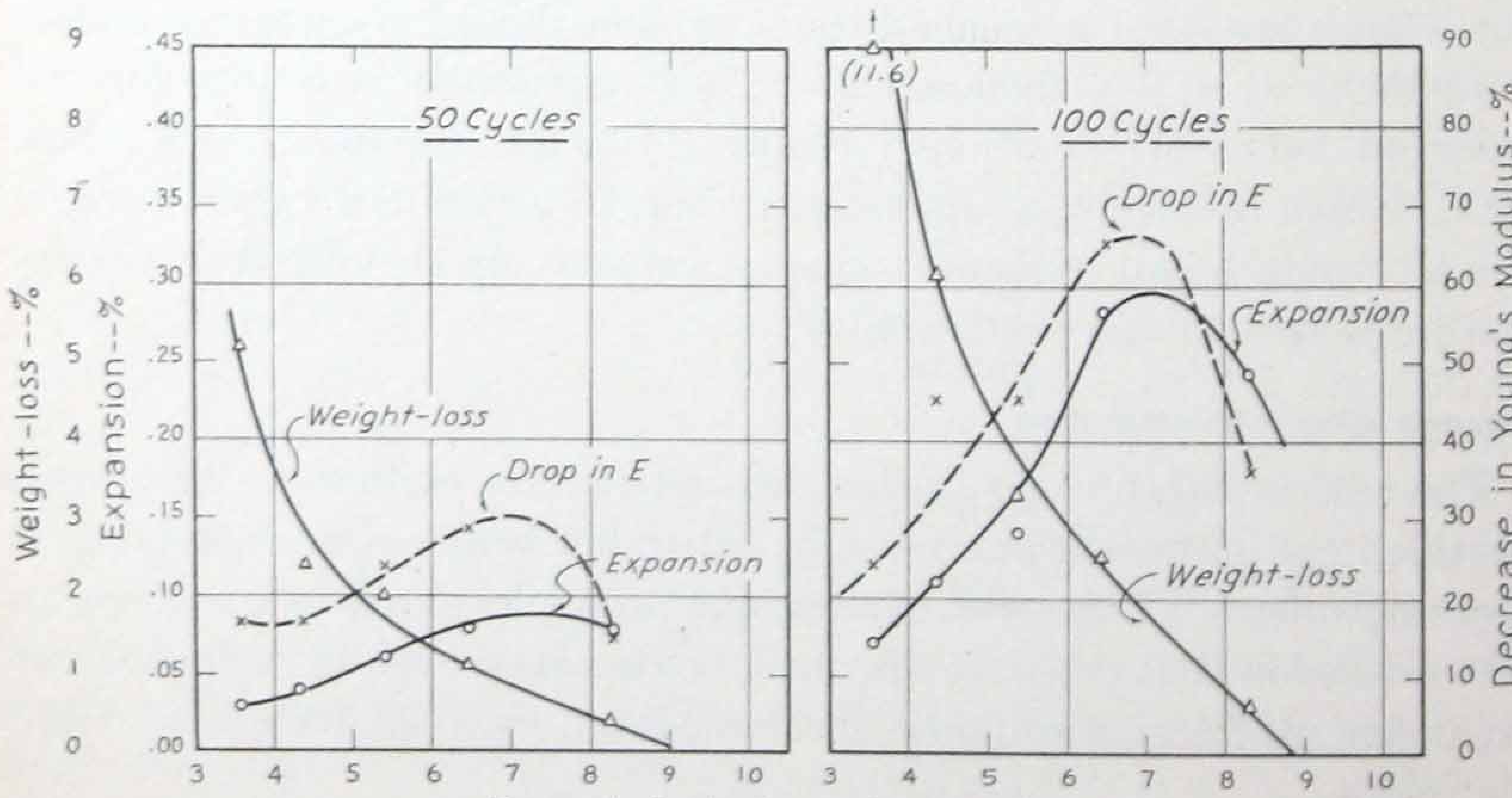


Fig. 2—Results of freezing and thawing tests of concrete having 3 to 4 inch slump

seem to reflect the relative permeabilities and hence rates of absorption, as would be expected, but the relative expansions and losses in resilience seem to require the explanation given above.

These particular specimens contained some unsound chert and thus a true explanation may have to include this factor also. However, a smaller group of tests using wholly sound aggregate gave results similar to these. Hence, it seems very doubtful that the small amount of disruptive aggregate can account for the result shown. These data therefore are regarded as showing the effects of dilation of the paste itself.

Influence of cavities

The discussion up to this point has carried the tacit assumption that the submicroscopic pores in the partially desiccated paste are the only spaces available for the movement of water during freezing. If this were the usual condition, concrete would show a very inferior resistance to weathering. Ordinary concrete contains many air-filled cavities that are not in direct communication with the surface. These cavities are entrained air bubbles, accessible pores in the aggregate particles, and thin fissures under the aggregate particles. The fissures, formed during the period of bleeding, are at first water-filled but may become partially or wholly emptied as hydration proceeds. Such fissures are more numerous and larger the leaner the concrete and the greater the slump of the fresh mix.

All empty cavities of the kind mentioned, especially air bubbles, are difficult to fill with water. They cannot be filled by capillary action (by soaking) because a liquid cannot spontaneously flow from a small capillary to fill a larger one. However, water can be forced into a cavity by applying external pressure or by pumping the air out of the previously dried specimen before admitting water. Under normal conditions a pressure exceeding one atmosphere is required to fill a cavity, because as the cavity fills its contained air becomes compressed. The pressures generated during freezing are probably more than sufficient to force water into such spaces.

It might at first seem that the amount of space required to protect concrete would depend on the amount of expansion to be accommodated. However, this is not the case, as will now be explained.

As shown in the examples previously given under "Crumbling and Spalling", the freezable water content of saturated concrete would ordinarily lie between 0.07 and 0.10 cu. ft. per cu. ft. of concrete, and the expansion of the water on freezing would be roughly 0.007 to 0.010 cu. ft., or 0.7 to 1.0 per cent of the volume of the concrete. Therefore, if the concrete contains 0.7 to 1.0 percent air-space, the expansion can,

theoretically, be accommodated. If the space is air-filled at a pressure of one atmosphere, and if we assume that the concrete can withstand 170 atmospheres (2500 psi.) of hydraulic pressure, then we need to provide space equal to the volume expansion plus 1/170 of that volume for compressed air which is negligible. That is, we need allow space equal to only slightly more than 0.7 to 1.0 percent of the volume of the concrete to accommodate the expansion. Since concrete ordinarily contains at least this much air-filled space, it should be able to withstand freezing and thawing almost indefinitely. Such a conclusion is obviously contrary to fact.

The figures just considered show that if the destructive action of freezing is due to hydraulic pressure, the resistance to *movement* of water must be the primary source of pressure, for practically all concrete contains enough air-filled space to accommodate the water-to-ice expansion. Hence, the distance between air spaces rather than the total volume of air space would be the factor determining the degree of protection, provided the total space is at least 1 percent or thereabouts.

As will be seen further on in this discussion, the destructive expansion could be accounted for by a modification of Taber's hypothesis, that is, by assuming that the damage is caused, not by hydraulic pressure, but by the growth of submicroscopic bodies of ice analogous to ice lenses. This would account nicely for the fact that concrete containing enough space to accommodate the ice-to-water expansion may nevertheless be damaged on freezing. However, it would fail to provide a very convincing explanation for the fact that introducing more air spaces prevents or greatly reduces damage by frost action. This is a reason for attempting to develop a hypothesis from a premise not involving direct crystal pressure.

To this phase of the hydraulic-pressure hypothesis there is the following important corollary:

Given a total air space greater than the possible amount of expansion, the protection of the concrete will be greater the smaller the average size of the individual air spaces.

This follows from the fact that for a given volume of air held within prescribed boundaries, the air being divided into a large number of separate units, the greater the number of units the closer together they must be.

The equally important converse of the corollary is this:

For a given degree of protection, the smaller the air-filled cavities the smaller the total volume of air required.

Experience shows that if concrete contains a large number of small, well distributed air cavities, as it does after it has been mixed in the

presence of a foam stabilizer, its rate of disintegration and rate of internal damage can be reduced to a small fraction of the usual rate. In terms of the matters discussed above, this is seen to be the result of providing ample room for expansion *and of limiting the thickness of the permeable material through which the water must move to find escape from ice pressure.* Other effects may be involved in this case, but they need not be considered in connection with this hypothesis.

This hypothesis provides an explanation for some of the results reported by Kennedy.* He found that neat cement prisms containing entrained air failed in a freezing and thawing test more rapidly than did a companion specimen containing virtually no air. The published photographs suggest that unlike air entrained in mortar or concrete, the air in these specimens collected in a relatively small number of large cavities separated by thick layers of paste. As can be seen from the above discussion, such cells would offer relatively little protection. In fact, once the wall of a large cavity is ruptured, water (or in this case $CaCl_2$ brine) can flow in and thus transform the cell from a source of protection into a source of disruptive pressure.

Relative permeabilities of paste and aggregate

If the aggregate particles in a specimen of concrete are less permeable than the paste, then they should increase the intensity of hydraulic pressure in the region where the paste is saturated, since, for a part of the freezable water, they block the most direct path to the unsaturated region. On this basis one would expect concrete containing impermeable aggregate to tend to fail along aggregate surfaces under the action of freezing. This has been pointed out previously by W. C. Hansen.†

If the concrete contains unsaturated aggregate particles that are more permeable than the hardened paste, those particles should moderate the hydraulic pressure somewhat as cavities do, *until the particles become saturated.* When the particles are saturated, water must escape into the surrounding paste during freezing or pressures will develop that are high enough to disrupt the aggregate particles and the surrounding material. The intensity of the pressure in saturated particles thus depends on the permeability of the paste that lies between the particles and the unsaturated region.

Influence of the initial degree of saturation

In an earlier part of the discussion it was stated that when concrete is partially dried, the initial freezing point or, more accurately, the final melting point is lower the greater the degree of dryness of the specimen. The final melting point is, in fact, a function of the relative vapor pressure

*Henry L. Kennedy, "The Function of Entrained Air in Concrete," ACI JOURNAL, June, 1943; *Proceedings* V. 39, p. 529.

†Office memorandum, Portland Cement Association, Research Laboratory.

of the water remaining in the specimen. Thus, the degree of saturation not only determines the severity of the effect of freezing, as discussed above, but also determines the maximum temperature at which ice can exist within the specimen.

A specimen that has been cured without gain or loss of water, that is, one that has been sealed after casting, would show a final melting point lower than the normal melting point of the "cement-solution" which it contains; the lower the water-cement ratio and the greater the extent of hydration the lower would be the final melting point in a specimen cured in this manner. Well hydrated, sealed specimens of low water-cement ratio probably contain no water that is freezable at temperatures normally experienced in this climate.

When specimens have access to an outside supply, they tend to absorb water during the course of hydration, as evidenced by their increase in weight. Specimens of high water-cement ratio are able to absorb nearly enough water to compensate for the contractions accompanying hydration; specimens of ordinary dimensions and low water-cement ratio are not able to do so except during the early stages. Thus, the resistance of rich specimens to *surface disintegration* is accounted for by their lesser degree of saturation.

Factors governing the amount of water absorbed during thawing

It seems fairly evident that the life of a specimen in a freezing and thawing test depends on its initial degree of saturation and to a marked degree on the rate at which it can absorb water. One of the factors involved in this is the mode and rate of thawing.

If the surface of a frozen specimen is covered with ice, the specimen cannot absorb water through that surface until the ice-coating melts. After the outside ice has melted, the rate of absorption should depend partly on the amount of pressure-deficiency, i.e., the negative pressure, within the specimen. This should depend on several factors, as will now be shown.

On freezing a specimen that is in contact with ice, hydraulic pressure is created that drives water inward or into cavities adjacent to the frozen regions, as already explained. When the temperature of a frozen specimen is raised, thawing inside the specimen begins immediately, no matter how low the temperature, and the last ice will melt at a temperature *below* the melting point of the ice covering the surface. The time available for this melting inside the specimen before the outside ice melts is believed to be a significant factor. If heat is received rapidly by the surface region, most of the outside ice may be melted before all the ice in the specimen disappears, owing to the steepness of the temperature gradient. However, if heat is received slowly, a layer of ice will remain

on the surface and thus maintain a constant temperature of 32 F for a considerable period.

Under these conditions of thawing, heat flows into the specimen through the outside layer of ice. Hence, melting within the specimen will first occur near the surface of the specimen and thus produce a layer of melt between the outside ice and the still-frozen interior. The *contraction* accompanying melting should create a negative pressure in this layer and thus as melting proceeds the water should flow toward this region. *As long as the outside remains sealed with ice, all such flow must be back from spaces into which the water was originally displaced.* Thus, in this circumstance the original distribution of the water tends to be restored during the period of thawing. If water from the outside becomes available before thawing on the interior is completed, *then water should be absorbed whether the specimen has become permanently dilated or not.* The rate of absorption will, of course, depend upon the difference in pressure and on the permeability of the material. Specimens of low water-cement ratio seem to absorb very little water during the thawing periods. However, existing data are unsatisfactory on this point because measurements of the weight of the specimen indicate only the net results of any losses due to disintegration and gains due to absorption of water.

The fact that the melting of the ice in the specimen may precede the melting of the outside ice probably is one important factor accounting for the resistance to disintegration or scaling of concrete containing an air-entraining agent. Because of the sequence of events as described, even the air-filled cavities just under the surface tend to be emptied before any water from the outside is available to them. If this were not true, it would be difficult to account for the resistance to scaling shown even by the troweled surface of concrete containing entrained air.

Freezing and thawing in $CaCl_2$ brine has been found to be more destructive than freezing and thawing in water. In terms of the hypothesis, a specimen frozen in brine should be able to absorb more liquid during the thawing period than one frozen in water; hence, the rate of disintegration in brine should be greater than in water. The greater absorption is due to the lower melting point of the brine. A 10 percent $CaCl_2$ brine, for example, will be fully melted at about 22 F. Since most of the ice within the specimen melts above this temperature, it follows from considerations already given that the portion of the thawing period during which liquid from the outside can be absorbed is relatively large for the specimens frozen in brine.

Experimental evidence that the amount of absorption per cycle in brine is greater than it is in water can be found in data published by

Hansen.* In Hansen's tests the specimens were given 100 cycles in water and then a 10 percent $CaCl_2$ brine was substituted for the water for the rest of the cycles. During the cycles in water many of the specimens showed very little change in weight after the first 5 cycles. As soon as the brine was substituted for the water, the amount of absorption per cycle for these specimens showed a marked increase. In this case, the specimens that withstood the first 100 cycles in water also stood up well in the subsequent cycles in brine, so that the increased rate of absorption observed was not clearly connected with an increased rate of disintegration. However, the result seems to account at least in part for the generally greater severity of the test when specimens are frozen in brine instead of water.

Effect of thickness of outside layer of ice

It is possible that the thickness of the ice layer formed on the outside of the specimen is one of the factors influencing the number of cycles of freezing and thawing required to produce a given degree of disintegration. This follows from the consideration given above: the thicker the layer of ice, the longer will be the period during which the temperature at the surface of the specimen remains at 32 F and therefore the more nearly will the pressure differences within the specimen produced on melting be equalized before outside water becomes available. To produce uniform results in a freezing and thawing test in which the specimens are surrounded with water, it therefore seems important to control carefully the amount of ice allowed to form around each specimen. If follows also that conditions of thawing should be carefully regulated so that all specimens receive heat at the same rate.

When the practice is followed of freezing the specimens in air and thawing them in water, a maximum of opportunity for absorption of water from an outside source is provided since there would be little if any ice on the surface to keep the specimen sealed while thawing. This would be a factor tending to hasten the process of surface disintegration. However, the lack of an ice-seal might reduce the effect of freezing, for pressures might be relieved by flow to the outside of the specimen as well as toward the interior.

Data published by Hughes† indicate that freezing in air and thawing in water is less destructive than freezing in water and thawing in water. This would indicate, according to the above paragraph, that the opportunity for water to escape to the outside while freezing in air protects the specimens more than the free access to water during thawing harms them.

*W. C. Hansen, "Influence of Sands, Cements, and Manipulation upon the Resistance of Concrete to Freezing and Thawing." ACI JOURNAL, Nov. 1942; *Proceedings* V. 39, p. 105 (1943).

†C. A. Hughes, "The Durability of Cement Mortars; the Cement and Method of Testing Major Variables," *Proc.* A.S.T.M., 33, Part II, 511 (1933).

Nature of the negative pressure in concrete

When freezing occurs in a saturated region and water is forced from that region to another, the water content of the saturated region will be lowered about 10 percent, if no expansion of the solid occurs. If the region entered by the displaced water contained air, the air would be compressed. For example, with an air-entraining cement, any water forced into one of the many air-cells would compress the air in that cell. When thawing occurs, the contraction lowers the pressure in the thawed region below that in the cavity into which the water was forced, as explained before. Some of the pressure difference may thus be due to compressed air, but probably this is a small part of the total force acting; capillary force probably accounts for the greater part of the total. This may be shown by the following example based on experimental data.

Consider a saturated region containing one gram (=1 cc.) of liquid water. We will assume that ⅔ g. of the water is freezable under the conditions of the test. Hence, the expansion on freezing will be $\frac{1}{10}$ of ⅔, or 0.07 cc. When this amount of water is displaced from the saturated region, the water content of the region will thereby be reduced to 0.93 g. When melting occurs, the region will therefore appear to be "dried" to the extent indicated. From other data it is known that such a decrease in water content would be accompanied by a small lowering of the vapor pressure. A given lowering of the vapor pressure is indicative of the magnitude of capillary force tending to drive water toward the partially dried region. If, for example, the vapor pressure is 98 percent of the saturation pressure, the maximum capillary force is 28 atmospheres (400 psi.). Thus, if an air cell contained water having a relative vapor pressure of 100 percent and the surrounding region contained water having a relative vapor pressure of 98 percent, a counteracting pressure of 28 atmospheres would have to be exerted to prevent water in the cell from entering the region. It therefore seems possible that capillary effects determine the direction and rate of water movement during the thawing period.

Rate of freezing

As mentioned before, the intensity of the hydraulic pressure that is developed during the freezing of a not wholly saturated specimen depends on the rate of movement of the water, or in other words, on the rate of freezing. Hence, it would seem that the higher the rate of cooling the more destructive the effect of freezing.

The rate of freezing in any part of the specimen should depend upon conditions external to the specimen and will not be the same in all parts of the specimen. The rates in general will depend on the rate of cooling as controlled by the amount, kind, and temperature of the refrigerant,

the amount of water surrounding the specimen, etc. The rate of freezing at a point in the specimen should depend on the distance of that point from the surface, the greater the distance the lower the rate of freezing. Since the intensity of the generated pressure depends on the rate of freezing, it follows that the greater the distance of a point from a surface the less the effect of freezing. Consequently, if the rate of freezing is controlled by the rate of cooling (no supercooling), the size of the specimen could have a considerable influence on the test results; the larger the specimen the smaller the internal damage caused by overstraining.

The Taber-Collins hypothesis

As mentioned before, Taber advanced a hypothesis to account for the expansion of soils that differs materially from that set forth above for concrete. Very recently an application of Taber's theory to the frost resistance of concrete has been published by Collins.* Collins concluded from his observations in the field and experiments in the laboratory that frost damage in concrete occurs by segregation of ice into layers in the concrete and that the layers exert pressure by growth in a direction opposite to the flow of heat. Collins' explanation is as follows:

> Cooling begins at the exposed surface and extends slowly inwards. When any layer below the surface reaches a sufficiently low temperature, the water in the largest pores begins to freeze and the latent heat given up by it tends to maintain constant temperature at the point of ice formation. The ice crystals so formed are in contact with unfrozen water in the surrounding, smaller pores and, by drawing water from them, the crystals continue to grow.
>
> . . . The force exerted by ice will be perpendicular to the cold surface; and if the concrete is of low strength, a plane of weakness parallel to the cold surface will tend to form at the level at which the ice is forming.
>
> The water drawn in by the growing crystals of ice will come first from the largest unfrozen pores. As these become emptied, the supply will be restricted and the rate of growth of the ice will be checked. The evolution of latent heat will not then be sufficient to maintain the temperature constant at the point of ice-formation and the temperature will begin to fall once more.
>
> As there is then little or no water in the largest pores in the concrete immediately below the first ice layer, freezing will not begin again until either the temperature has dropped sufficiently to freeze the pores that do contain water or a level is reached where the larger pores are not affected by the ice forming above them. The result of this process is that concrete will contain a series of planes of weakness parallel to the surface of cooling. During the subsequent cycles of freezing the ice will again tend to form at the same levels as before, because the pores there have been distended by the previous ice, and the freezing point of the water in them will be higher than in the surrounding concrete.
>
> The damage to the concrete is considered to be caused not so much by the actual increase in volume of the water in the pores on freezing as by the growth of the crystals afterwards and the consequent segregation and concentration of ice into the layers.

---

*A. R. Collins, *J. Inst. Civil Engrs.* **23**, 29 (1944).

To substantiate this conclusion Collins made experiments on concrete cylinders, of the same kind that Taber made on soils. In these experiments the specimen is cooled at one end only while water, kept above the freezing temperature, is supplied at the opposite end. When using a very low-grade, porous cylinder of concrete, Collins observed the development of a horizontal crack about one inch below the top of the concrete cylinder and considered this to be analogous to the laminations which appeared in a soil cylinder under the same condition of test.

With respect to the effect of air-entraining agents Collins says: "The precise way in which these materials improve durability of concrete is not yet fully understood, but they are believed to act in one of two ways. They may change the pore structure of the concrete by entraining air or by forming bubbles of gas, or they may make the concrete itself water repellent. In either case the normal movement of moisture within the concrete is disturbed or restricted and the ability of the water to form ice layers is thereby apparently reduced."

Collins' observations of the behavior of concrete in the mild climate of England led him to the conclusion that concrete mixes so proportioned as to have a water-cement ratio of less than 0.7 by weight are able to withstand frost action.

DEFENSE OF HYDRAULIC PRESSURE PREMISE

As indicated in the introduction, the writer has no desire to try to refute the Taber-Collins hypothesis*; on the contrary, he feels that it should be kept in mind and that experiments should be made to test the premise on which it is based. If still other hypotheses can be devised, so much the better, as far as progress toward a correct understanding of this question is concerned. However, to justify offering a hypothesis that is in basic disagreement with the ideas set forth by Collins, some discussion of the Taber-Collins hypothesis is advisable.

Although Taber's hypothesis seems highly satisfactory for explaining frost heaving in soils, there are several reasons for believing that it should not be applied to concrete or at least not to concrete frozen under the usual laboratory conditions. Some of these reasons rest on direct evidence; some on inference.

Possibly the most direct evidence against the Taber-Collins hypothesis is found in a paper published by Mattimore.† In this paper data are given showing that in laboratory tests the *lower* the rate of freezing the *smaller* the destructive effect, whereas the Taber-Collins hypothesis requires the opposite result.

*This designation is used for convenience. The writer does not know whether Taber has ever applied his hypothesis to concrete or whether he would endorse such an application.

†*Proc.* Highway Research Board *16*, 135 (1936).

Inferred evidence against applying the Taber hypothesis to concrete comprises those factors and observations indicating that concrete must freeze as a "closed system," whereas segregation of ice can occur only in "open systems." Taber defined a closed system as " . . . systems from which water could not escape and into which water could not enter,"* Leading to this definition is the observation that when a liquid freezes in a porous system, unfrozen liquid at a higher temperature tends to flow toward the ice that is first formed and thereby to promote the growth of the first-formed ice crystals. When water is available and able to flow freely enough to the point of initial ice formation, ice will not form at a lower level as long as this condition persists. The condition of flowing "freely enough" is one in which the heat given up by the water on freezing is enough to maintain constant temperature.

When the heat is conducted from the region of initial ice formation considerably faster than it can be transferred to that region, then the water in the specimen freezes in place and lenses do not form. Regardless of whether or not outside water is available to enter the specimen, Taber calls the condition first described "freezing in an open system," and the one next described "freezing in a closed system."

Taber observed that with respect to ice segregation, "The chief factors are: size and shape of soil particle, amount of water available, size and percentage of voids, rate of cooling, and surface load or resistance to heaving." These are the factors that determine the permeability of the soil, its thermal conductivity, the amount of latent heat released on freezing, per unit volume of soil, and the mechanical force acting against the expansion of the ice.

Concrete differs widely from soil with respect to some of these properties. Ruettgers, Vidal, and Wing† show the permeability of concrete to range from about 16×10^{-8} ft. per day for concrete having a water-cement ratio of 0.44 (5 gal. per sack) to $14{,}000 \times 10^{-8}$ for w/c = 1.0 (11 gal. per sack). Dimitri Krynine‡ gives the permeability of clay as ranging from 0.48 ft. per day ($48{,}000{,}000 \times 10^{-8}$) to "practically zero." Plummer and Dore** give the permeability of clay as "less than 0.00024 ft. per day" ($24{,}000 \times 10^{-8}$). Taber found that the less permeable clays froze as closed systems, that is, there was no segregation of ice even without a superimposed load. Since Taber did not publish the permeabilities of these clays, it is not certain whether their permeabilities were "practically zero" or somewhat higher. Yet it is clear that all but the very leanest concretes must have what the soil tester would judge by his method of test to be practically zero permeability. Among such concretes the

*J. Geol. 38, 303 (1930).
‡*Soil Mechanics* (McGraw-Hill, 1941) p. 60.
†*Ibid.* p. 395, Fig. 8.
**Fred L. Plummer and Stanley M. Dore, *Soil Mechanics and Foundations* (Pitman, 1940) p. 45.

degree of impermeability alone precludes the formation of lenses under the usual rates of cooling. Even for the leanest of practical concrete, which for want of definite data must be assumed to have permeabilities possibly as high as some clays, we must conclude that lens formation is highly improbable because of other factors discussed below.

When ice tends to expand by lens growth, it meets much more resistance in concrete than it does in unloaded soil. The ice first formed in concrete could occupy not over 10 percent of the cross-section. This ice cannot grow to form a lens unless it can first disrupt the capillaries in which it forms. The force required for disruption will depend on the tensile strength of the concrete. As shown earlier, this force could probably be as high as 2500 psi.

In soils the voids run upwards of 35 percent. Therefore, even for the same total force the unit pressure on the ice first formed in soil would be about ⅓ to 1/7 of that in concrete. It is very significant that Taber found that loading a soil often caused it to freeze as a closed system, whereas the same soil formed lenses when frozen unloaded. He says, "A relatively small surface load will entirely prevent frost heaving in an open system if the material is of such texture that only a little segregating ice forms under the most favorable conditions."

Thus consideration of permeability and resistance to expansion makes it appear that if any kind of soil freezes as a closed system, then all concrete should do so except perhaps when the rate of cooling is exceedingly low.

It would seem reasonable, however, to assume that ice segregation takes place in concrete on a submicroscopic scale. As already pointed out, the hardened paste is considered to be composed largely of a porous gel containing a system of capillaries. If the ice forms only in the capillaries, as seems likely, then we may imagine it to be forming in a container having porous, water-laden walls of gel. Hence, the ice could and probably would receive water from the walls as well as from the more open capillaries. The amount of water available from the gel is very limited; nevertheless some expansive force due to this effect is probable. In fact, we could have assumed that the expansion on freezing is due entirely to segregation on this submicroscopic scale but, as pointed out before, such an assumption does not lend itself readily to an explanation of the protective effect of air-filled cavities or the observed effect of increasing the rate of freezing. It would require the assumption that the cavities do not directly relieve the pressure but merely permit the solid material to yield under stress with less disruption. How almost complete immunity to frost action could be brought about through this mechanism is not very clear.

SOME GENERAL OBSERVATIONS

Two corollaries of this hydraulic-pressure hypothesis have been given; another will be mentioned here.

It is apparent that with sound aggregates, and with the concrete not initially saturated, the rate of surface disintegration depends mainly on *the porosity of the paste.* The porosity of the concrete as a whole depends on the porosity of the paste and on the paste content of the concrete. Since paste content is an independent variable, it follows that:

No general correlation between rate of disintegration and porosity of the whole concrete should be expected.

Seeming exceptions to this are the results reported by Hansen* where fairly satisfactory correlation between absorption and durability was found for cores cut from highways and specimens cast in the laboratory. However, the absorptions reported were the quantities of water taken up during two days of soaking, after only two days of drying from a previously soaked condition. Owing to the fact that the water lost during a two-day period of evaporation can be practically all reabsorbed in two or three hours, the values reported by Hansen must have depended on the *rate of evaporation* during the drying period. This, in turn, depended not primarily on the total evaporable water content (total porosity) but very largely on the *permeability* of the concrete. Hence, his correlations were virtually between permeability and rate of disintegration. Since the permeability of such concretes depends predominantly on the porosity of the paste, the correlation was virtually on the basis of paste-porosity.

The hypothesis supports strongly the contention of Scholer† and others to the effect that the degree of saturation (or the "saturation coefficient") is "of utmost importance." In fact we may conclude that the two factors that control the life of a specimen in a freezing and thawing test are its initial saturation coefficient and its permeability, together with these same factors for any unsound aggregate in the concrete. The actual life of the specimen will depend on the conditions that control its absorption of water during the test, as discussed above, assuming that the specimen as a whole was initially below the critical degree of saturation.

TESTING THE HYPOTHESIS

This hypothesis cannot be proved or disproved by data now at hand. To test the hypothesis, quantitative data on such factors as *initial degree of saturation* and *absorptivity* of the test specimens must be known.

---

*W. C. Hansen, "Uniformity of Cores an Indication of Pavement Quality," *Proc.* 20th Ann. Meeting Highway Res. Board, p. 568 (1940); ACI JOURNAL, Nov. 1942; *Proc.* 105 (1943).

†C. H. Scholer, "Durability of Concrete," Report on Significance of Tests of Concrete and Concrete Aggregates, 2d Ed., p. 29 (1943) A.S.T.M. Publication.

Without such quantitative information, one can use the hypothesis to explain *any* observed result, simply by making appropriate assumptions about the unknown quantities.

For example, more than once it has been observed that prolonging the curing period reduces the resistance of laboratory specimens in a freezing and thawing test. Such a result can be explained as follows: An increase in the amount of hydration has three possible effects:

(1) It reduces permeability.
(2) It reduces the amount of freezable water.
(3) It possibly increases the initial degree of saturation.

According to the hypothesis a reduction in permeability and an increase in degree of saturation are factors increasing the intensity of hydraulic pressure and are therefore detrimental to durability. On the other hand, the reduction in the amount of freezable water is beneficial. To account for the observed effect it is only necessary to assume that the effect of reducing permeability or increasing the initial degree of saturation, or both, outweighed the effect of the reduction in freezable water. To account for an *improvement* in resistance from prolonged curing, which also has been observed, it is only necessary to make the opposite assumption.

The principal incentive for formulating this hypothesis is the hope that those who have the necessary facilities will begin to accumulate such data as are required to support or refute the ideas set forth. This requires new knowledge of the properties of paste and of aggregate, particularly their relative permeabilities. It also requires data on the permeability and absorptivity of the concrete as a whole. It requires new studies of supercooling.

With respect to testing technique it requires close control of freezing and thawing conditions, particularly the rate of cooling, the minimum temperature reached, the amount of ice-coating, if any, and the length of time during which the surfaces remain at 32 F during the thawing period.

It requires an accurate measure of the degree of saturation of each specimen at the beginning of the freezing test and a study of the conditions that control the degree of saturation.

The hypothesis indicates also that entrained air should be more effective the smaller the bubbles. Hence, if there is any way to control bubble-size, it would be advantageous to make the bubbles as small as possible and thus minimize the total volume of air required, for to do so should hold to a minimum any adverse effect of entrained air on

strength. This aspect of the hypothesis calls for laboratory experiments along several lines.

Discussion of this paper should reach the ACI Secretary, in triplicate, by April 1, 1945, for publication in the JOURNAL for June 1945.